High domain wall velocities induced by current in ultrathin Pt/Co/AlOx wires with perpendicular magnetic anisotropy

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Abstract

Current-induced domain wall (DW) displacements in an array of ultrathin Pt/Co/AlOx wires with perpendicular magnetic anisotropy have been directly observed by wide field Kerr microscopy. DWs in all wires in the array were driven simultaneously and their displacement on the micrometer-scale was controlled by the current pulse amplitude and duration. At the lower current densities where DW displacements were observed ($j \leq 1.5 \times 10^{12}$ A/m^2), the DW motion obeys a creep law. At higher current density ($j = 1.8 \times 10^{12}$ A/m^2), zero-field average DW velocities up to 130 ± 10 m/s were recorded.

Magnetic domain wall (DW) propagation by spin-polarized current, predicted by Berger [1], has attracted huge attention in the last few years (see [2, 3] and references therein) due to unsolved questions about the underlying wall propagation mechanism and the possibility of applications in spintronic devices [4]. Up to now current-induced domain wall motion has been mainly studied in flat nanoscale strips or "wires" of NiFe (Permalloy) [5, 6, 7, 8] where the magnetization is oriented along the length of the wire. However, the potential disadvantages of using Permalloy wires in devices include the difficulty of achieving fast, controllable DW motion, and the large drive currents required. Although a DW velocity due to current of 110 m/s has been reported [7, 8], it has also been demonstrated that the DW motion is stochastic due to thermal effects and local pinning [9], and that the DW may undergo spin structure transformations [10], leading to complex dynamics. Micromagnetic simulations have shown that in metallic wires with perpendicular magnetic anisotropy, these problems may be overcome [11, 12]. However, in very few experiments on wires with perpendicular anisotropy have current-induced DW displacements been observed, probably due to the strong intrinsic pinning. In experiments that have shown current-induced DW displacements the DW velocities are generally smaller than in Permalloy, e.g. Tanigawa et al. [13] obtained a DW velocity of 0.05 m/s in a CoCrPt wire, while Koyama et al. [14] reported 40 m/s in a Co/Ni wire.

We study current-induced DW motion in Pt/Co/AlOx nanowires and compare the results with similar measurements on Pt/Co/Pt wires. In these systems the magnetization in the Co layer points out of the plane [15, 16], narrow ($\sim$10 nm) Bloch-type DWs occur and a high spin torque efficiency is

expected [11, 12]. Apart from the top layer (AlOx or Pt), the two types of nanowire in our study have the same structure. The presence of the AlOx in the Pt/Co/AlOx system, breaking the inversion symmetry, is expected to enhance the spin torque via an increase of the spin flip rate, and this effect was recently evidenced for DW displacements on the order of a few nanometers [17]. In this Letter, we examine the effect of this symmetry breaking on micrometer-scale DW displacements.

The nanowires are 500 nm wide and approximately 10 μm long, patterned from magnetron sputtered films of Pt(3nm)/Co(0.6nm)/AlOx(2nm) or Pt(3nm)/Co(0.6nm)/Pt(3nm) on Si/SiO$_2$(500nm) by electron beam lithography and Ar ion etching. Twenty wires are arranged in parallel with a repeat distance of 2 μm and connected at each end to a micrometer-scale domain nucleation pad. Fig. 1(a) shows part of the wire array. An Au contact is defined by optical lithography on top of each nucleation pad, giving a total wire array resistance ~ 100 Ω.

The magnetization of the wire array is saturated out-of-plane in an external field of about 4 kOe, and then applying a reverse field, DWs nucleated in the pads propagate into the wires. By precisely controlling the field strength, DWs are positioned in the wires (Fig. 1(a)). Subsequently the field is decreased to zero and a number of current pulses n (nominal pulse length $t = 0.8 - 5$ ns, density j up to 1.8×10^{12} A/m^2) are injected into the wires via the Au contacts.

Using wide field Kerr microscopy in differential imaging mode, the current-induced displacement of DWs in the Pt/Co/AlOx wires was directly ob-

served. Fig. 1(b) shows two Pt/Co/AlOx wires with two DWs in each wire. The image is the difference between the domain pattern in the initial state and in the state after the current pulse has been applied, and thus there is contrast only in regions where the magnetization in the wire has reversed from one direction to the other. The initial wall positions are marked by dotted lines and the electron flow is from right to left. The displacement of the DWs gives black or white contrast depending on whether the magnetization reverses from "up" to "down" or vice versa. The DW displacement can be controlled by varying the amplitude or length of the current pulse or the number of pulses. When the current direction is reversed, DW motion continues to be opposite to the direction of electron flow (i.e. also reversed) and DW displacements are of the same magnitude. These results for Pt/Co/AlOx wires are in contrast with measurements on Pt/Co/Pt wires, where DW displacements were not observed. The only effect of the current in the Pt/Co/Pt wires was, for sufficiently long pulses of high amplitude (e.g. $t = 5$ ns, $j = 1.6 \times 10^{12}$ A/m^2), to nucleate reverse domains at random locations along the wire due to Joule heating.

Domain nucleation is also observed in the Pt/Co/AlOx wires, but only if the current pulse is long enough. In these wires the rate of Joule heating is not as high because an insulating AlOx layer has replaced the Pt top layer and thus less current is required for a given j. If the current pulse is short (e.g. $t = 0.8$ ns), thermal equilibrium is unlikely to be reached and the temperature T of the wire remains well below the Curie temperature ($T_C \sim 500$ K). The evidence for this is that we do not observe domain nucleation even at the highest current density in the Pt/Co/AlOx wires.

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In the experiment we decrease the pulse length as the current density is increased in order to ensure that $T << T_C$.

We capture ten images of DW displacements in the Pt/Co/AlOx wires for each value of current density. Fig. 2 shows probability distributions, each built from approximately 200 DW motion events, of the DW velocity for different values of current density. At $j = 1.0 \times 10^{12}$ A/m^2, the lowest current density for which DW displacements were observed, 500 pulses of 5 ns duration were required in order to produce a DW displacement on the order of $\Delta = 500$ nm. This corresponds to low DW velocities of $v = \Delta/(nt) = 0.27 \pm 0.02$ m/s on average, as shown in Fig. 2(a). Meanwhile, for $j = 1.8 \times 10^{12}$ A/m^2, the highest attainable current density in this experiment, only ten pulses of 0.8 ns duration were needed to cause a DW displacement exceeding 1 μm, corresponding to an average DW velocity of 68 ± 1 m/s (Fig. 2(b)).

As the current density increases, the DW velocity distribution changes from one that is skewed towards low velocities (Fig. 2(a)) to one that is more symmetric (Fig. 2(b)). Additionally, the width of the distribution decreases (inset of Fig. 2(a)). The large width of the distribution at low current densities indicates that in this regime the DW motion is predominantly stochastic; then as j increases, the decreasing width implies that the DW motion becomes more reproducible.

The mean DW velocity v appears to increase exponentially as a function of the current density (Fig. 3(a)), suggesting that in the measured range of j the DW exhibits creep motion described by [18]:

$$v = v_0 \exp\left[- \left(\frac{T_{dep}}{T}\right)\left(\frac{f_{dep}}{f}\right)^{\mu} \right].$$ (1)

Here, T_{dep} is the depinning temperature given by U_C/k_B, where U_C is related to the height of the DW pinning energy barrier, f_{dep} is the depinning force ($\equiv j_{dep}$, the depinning current density), v_0 is a numerical prefactor and μ is a universal dynamic exponent equal to 1/4 for a 1D interface moving in a 2D weakly disordered medium [18]. To check whether our DW motion obeys the creep law, we plot $\ln v$ versus $j^{-1/4}$ (Fig. 3(b)). Linear behavior is seen at the lower current densities $j = 1.0 - 1.5 \times 10^{12}$ A/m^2, which verifies not only that DW creep occurs in this regime, but also that $\mu = 1/4$ holds true for our system.

At $j \approx 1.5 \times 10^{12}$ A/m^2 there is a deviation from the creep motion; although the DW velocity continues to increase with further increasing current density, it increases less rapidly than expected by the creep law. The deviation from creep motion cannot be explained by sample heating since in this case the creep law would predict even higher velocities. A possible explanation is that at $j \approx 1.5 \times 10^{12}$ A/m^2 the DW motion starts a transition from the creep to a viscous flow regime [16]. This would result in smaller DW velocities than expected by the creep law in the range $j = 1.5 - 1.8 \times 10^{12}$ A/m^2.

Fig. 3(a) also shows the maximum DW velocities measured at each current density. A top speed of 130 ± 10 m/s (average over ten pulses) was recorded at $j = 1.8 \times 10^{12}$ A/m^2, which is large compared to previously reported values for wires with perpendicular anisotropy [13, 14]. These high DW velocities are surprising, given the difficulty of displacing DWs in the same manner in Pt/Co/Pt wires. It is reasonable to expect that the explanation for this stems from the presence of the Co/AlOx interface. Recently the ratio of the

non-adiabatic and adiabatic spin torque components, β, representing the spin torque efficiency, has been experimentally determined to be of the order of 1 in Pt/Co/AlOx [17], and at least 50 times smaller than this in Pt/Co/Pt. The reason for the difference in β is thought to be an increase in the spin flip rate at the Co/AlOx interface [17]. As β controls the DW motion, this difference could explain the fact that DW displacements are only seen in Pt/Co/AlOx wires, and that the DW velocities there are high.

In summary, we have studied DW motion in ultrathin Pt/Co/AlOx nanowires induced by nanosecond current pulses. DW displacements on the micrometer-scale were observed, and could be controlled by varying the amplitude or length of the current pulse, or the number of pulses. In the current density range $j = 1.0 - 1.5 \times 10^{12}$ A/m^2 the DWs exhibit stochastic creep motion, whereas at higher current densities in the range $j = 1.5 - 1.8 \times 10^{12}$ A/m^2 the DW motion is more reproducible and velocities greater than 100 m/s were measured, indicating a large spin torque efficiency in this material. This result offers a route to the realisation of magnetoelectronic devices based on current-induced DW motion.

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Figure captions

Figure 1. (a) Wide field Kerr microscope image of part of the Pt/Co/ AlOx wire array, with Au contacts shown schematically. The wires are approximately 10 μm long. The boundaries between dark/light contrast in the wires indicate the DW positions. (b) Differential Kerr microscope image of current-induced DW displacements in 500 nm-wide Pt/Co/AlOx wires, driven by 10×1.5 ns current pulses of density $j = 1.7 \times 10^{12}$ A/m^2.

Figure 2. Probability distributions of current-induced DW velocity in 500 nm-wide Pt/Co/AlOx wires, for different values of current density (a) 1.0×10^{12} A/m^2 and (b) 1.8×10^{12} A/m^2. The mean DW velocity is indicated in each figure by a dashed line: (a) 0.27 m/s, (b) 68 m/s. The inset in (a) shows the ratio of the standard deviation σ of the distribution to the mean velocity v as a function of the current density j.

Figure 3. (a) Mean and maximum DW velocity as a function of current density for 500 nm-wide Pt/Co/AlOx wires. The error bars are smaller than the data points unless shown. (b) The mean DW velocity v fits to a creep law at current densities $j = 1.0 - 1.5 \times 10^{12}$ A/m^2 (corresponding to $j^{-1/4} = 0.9 - 1.0$ ($\times 10^{12}$ A/m^2)$^{-1/4}$).
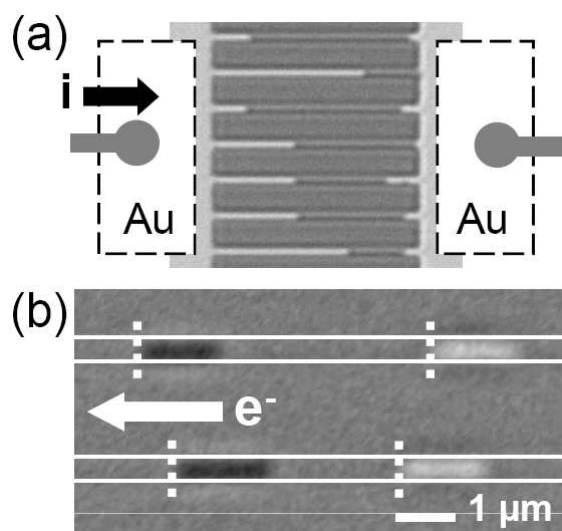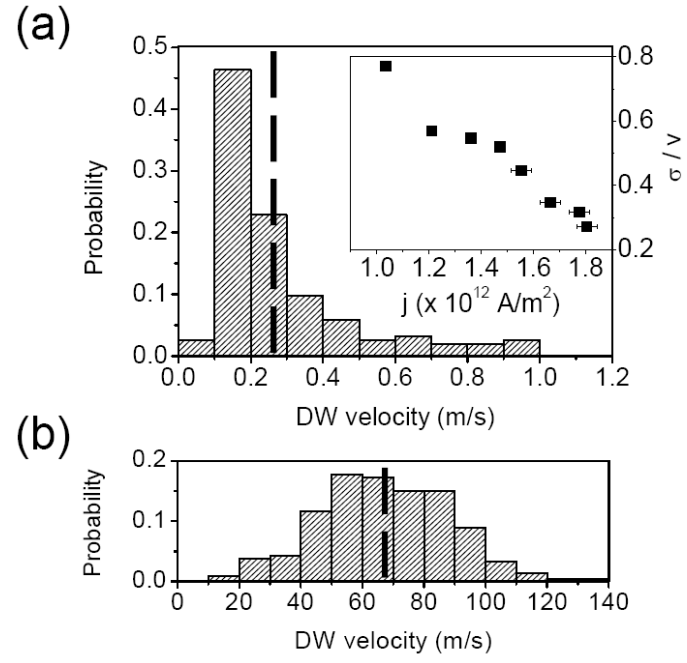
Figure 1.

(a)
i

Au   Au

(b)
e⁻

1 μm

Figure 2.

Figure 3.